

Inflated planets and their low-mass companions

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Abstract. Various mechanisms have been proposed to explain the inflated size of HD 209458b after it became clear that it has no companions capable of producing a stellar reflex velocity greater than around 5 m s^{-1} . Had there been such a companion, the hypothesis that it forces the eccentricity of the inflated planet thereby tidally heating it may have been readily accepted. Here we summarize a paper by the author which shows that companion planets with masses as low as a fraction of an Earth mass are capable of sustaining a non-zero eccentricity in the observed planet for at least the age of the system. While such companions produce stellar reflex velocities which are fractions of a meter per second and hence are below the stellar jitter limit, they are consistent with recent theoretical work which suggests that the planet migration process often produces low-mass companions to short-period giants.

1. Introduction

Of the fourteen transiting extrasolar planetary systems for which radii have been measured, at least three appear to be considerably larger than theoretical estimates suggest. It has been proposed by Bodenheimer, Lin & Mardling (2001) that undetected companions acting to excite the orbital eccentricity are responsible for these oversized planets, as they find new equilibrium radii in response to being tidally heated. In the case of HD 209458, this hypothesis has been rejected by some authors because there is no sign of such a companion at the 5 m s^{-1} level, and because it is difficult to say conclusively that the eccentricity is non-zero. Transit timing analysis as well as a direct transit search have further constrained the existence of very short-period companions, especially in resonant orbits. Whether or not a companion is responsible for the large radius of HD 209458b, almost certainly some short-period systems have companions which force their eccentricities to nonzero values. This paper is a summary of Mardling (2007) which is dedicated to quantifying this effect.

The eccentricity of a short-period planet will only be excited as long as its (non-resonant) companion's eccentricity is non-zero. In fact, Mardling (2007) shows that the latter decays on a timescale which depends on the structure of the *interior* planet, a timescale which is often shorter than the lifetime of the system. *This includes Earth-mass planets in the habitable zones of some stars.* On the other hand, there exist parameter combinations (Q -value of the innermost planet, companion mass and semimajor axis) for which significant eccentricity in the short-period planet can be sustained for at least the age of the system, and these include systems with companion masses as low as a fraction of an Earth mass.

2. Inflated planets

The three largest planets discovered to date are HD 209458b (Charbonneau et al. 2000; Henry et al. 2000), HAT P1b (Bakos et al. 2006) and WASP-1b (Collier Cameron et al. 2007). Table 2. lists the measured attributes of these planets together with

Table 1. Inflated planet data

	a_p (AU)	m_p (M_J)	R_p (R_J)	e_p	τ_{circ} (Gyr)	age (Gyr)
HD 209458b	0.045	0.64	1.32	0.014	0.14	5.5
HAT P1b	0.055	0.53	1.36	0.09	0.33	3.6
WASP 1b	0.038	0.79	1.44	-	0.03	2.0

the estimated age and circularization timescales, the latter assuming a Q -value $Q_p = 3 \times 10^5$. It is clear from this data that if the eccentricities are real, some mechanism operates to maintain them since $\tau_{circ} \ll \text{age}$ in each case.

Bodenheimer, Laughlin & Lin (2003) and Burrows et al. (2007) calculated the rate at which energy needs to be deposited into a gas giant with a specified mass and age (and with and without a core) to maintain the observed radii of these planets. However, they assumed that the energy is distributed uniformly throughout the planet’s envelope and dissipated locally; if the energy is instead transported and dissipated close (but not too close) to the surface, a smaller deposition rate may be adequate. Consequently, Bodenheimer, Laughlin & Lin (2003) found that an eccentricity larger than that observed for HD 209458b is necessary to maintain the planet’s radius, at least for reasonable Q -values.

Here we assume $Q_p = 3 \times 10^5$, a value consistent with the analysis of Wu (2003) for all short-period gas giants discovered at that time, and assume that the estimated eccentricities of the planets in Table 2. are accurate. We will demonstrate that it is possible for extremely low-mass planets to maintain such eccentricities for at least the lifetime of the system.

3. Long-term eccentricity evolution

Figure 1(a) shows three-body secular evolution for an HD 209458b-like system with a companion planet of mass $0.1M_J$ at 0.4 AU. The eccentricity of both planets varies periodically with the period reducing when the post-Newtonian potential of the star is included. Figure 1(b) shows the evolution of the eccentricity of HD 209458b with the same companion but with tidal damping included. Here an artificially low value of $Q_p = 100$ was chosen to clearly illustrate the behavior. This time the eccentricity appears to evolve to a fixed value on a timescale of around 1.4×10^5 yr, which for $Q_p = 3 \times 10^5$ corresponds to 0.42 Gyr ($3\tau_{circ}$; see Mardling (2007) for details). The “equilibrium” or “fixed-point” eccentricity is given by

$$e_p^{(eq)} = \frac{(5/4)(a_p/a_c) e_c \varepsilon_c^{-2}}{\left| 1 - \sqrt{a_p/a_c} (m_p/m_c) \varepsilon_c^{-1} + \gamma \varepsilon_c^3 \right|}, \quad (1)$$

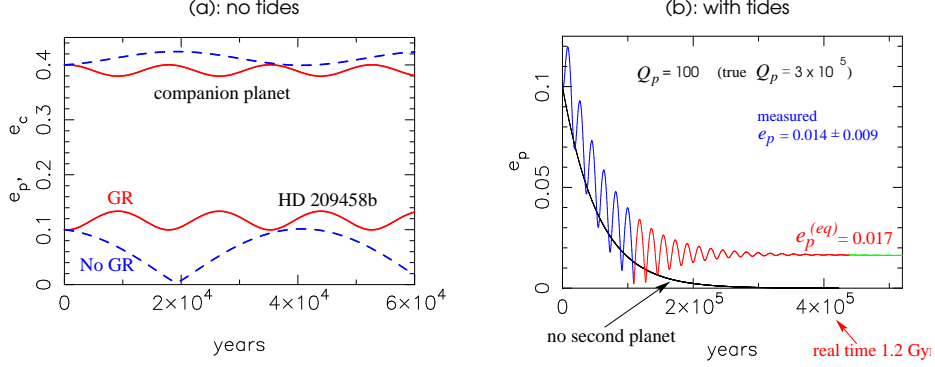


Figure 1. Secular evolution (a) without and (b) with tidal damping.

where a_p and m_p are the semimajor axis and mass of the observed planet, a_c and m_c are those of the hypothetical companion, e_c is its eccentricity, $\varepsilon_c = \sqrt{1 - e_c^2}$ and $\gamma = 4(n_p a_p / c)^2 (m_* / m_c) (a_c / a_p)^3$. Here n_p is the observed planet's mean motion, m_* is the star's mass and c is the speed of light. Capture by the fixed point is also accompanied by a transition from circulation to libration of the angle between the lines of apsides of the orbits.

While the system evolves to a (psuedo)-fixed point on the timescale $3\tau_{circ}$ (with very little change in e_c), in the long run the true equilibrium or fixed-point state of the system is two circular orbits. This occurs on a timescale which is given approximately by

$$\tau_c = (16/25)(m_c/m_p)(a_c/a_p)^{5/2} F(e_c^*)^{-1} \tau_{circ}, \quad (2)$$

where e_c^* is the value of e_c when the system first finds $e_p^{(eq)}$, and $F(e_c) = \varepsilon_c^3(1 - \alpha\varepsilon_c^{-1} + \gamma\varepsilon_c^3)^2$ with $\alpha = \sqrt{a_p/a_c}(m_p/m_c)$. In fact, in general (2) tends to underestimate the true circularization time of the system, and a much more precise estimate is available (Mardling 2007). The analysis leading to this also reveals that a different type of solution exists for very low-mass companions. Such a solution does not involve slow exponential decay of the eccentricities, but rather a slow *increase* of the observed planet's eccentricity to a maximum value before rapid decay to zero. Figure 2 demonstrates this behavior for a system with a companion mass of $4M_\oplus$, $a_c = 0.3$ AU and $e_c(0) = 0.7$. Such solutions have parameters which make $e_p^{(eq)}$ (equation (1)) near singular. Also shown is an analytical solution (Mardling 2007) and the approximate exponential solution with timescale (2). Clearly the latter now *overestimates* the timescale, however, for realistic values of Q_p this is still much longer than a Hubble time.

Figure 3 demonstrates that these “pathological” solutions are not actually rare, existing for a significant range of values of the companion mass and semimajor axis. Notice the extremely low-masses associated with some non-zero values of the observed planet's current eccentricity (assuming a system age of 5.5 Gyr). “Normal” (exponentially decaying) systems exist for larger companion masses and semimajor axes. Such low-mass solutions are consistent with the planet migration studies of Raymond, Mandell & Sigurdsson (2006) and Fogg & Nelson (2007).

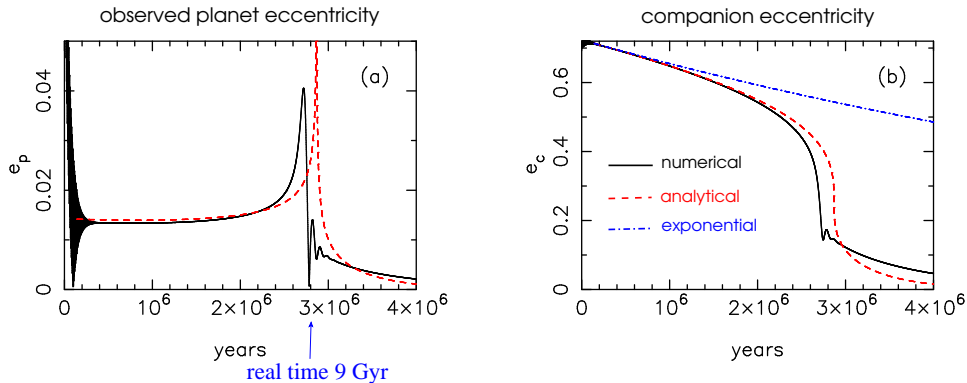


Figure 2. Pathological behavior of systems with very low-mass companions (see text for discussion).

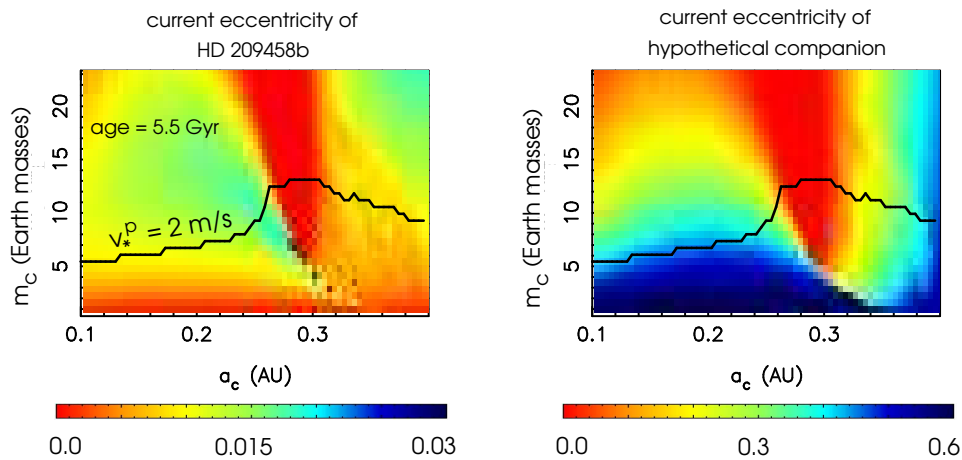


Figure 3. Eccentricities of HD 209458b and hypothetical companion at 5.5 Gyr for a range of companion masses and semimajor axes. v_*^p is the reflex velocity of the star due to the companion when it is at periastron. All systems except for those in the top right corners are of the type shown in Figure 2. Note non-zero values of HD 209458b eccentricity for $m_c < 1 M_\oplus$.

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